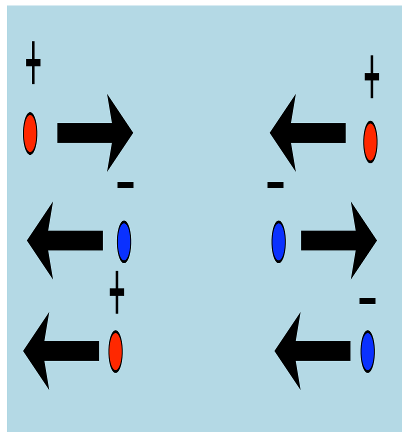
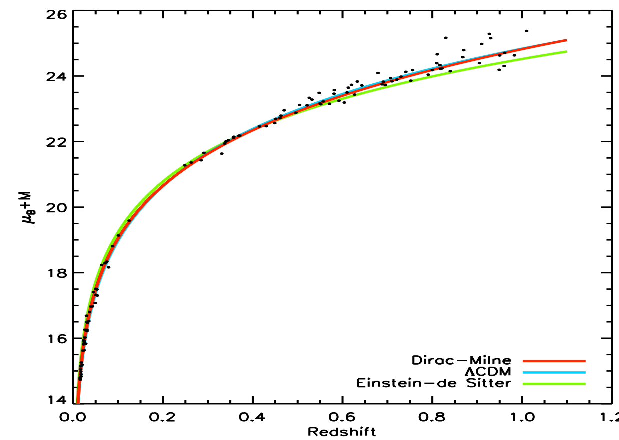
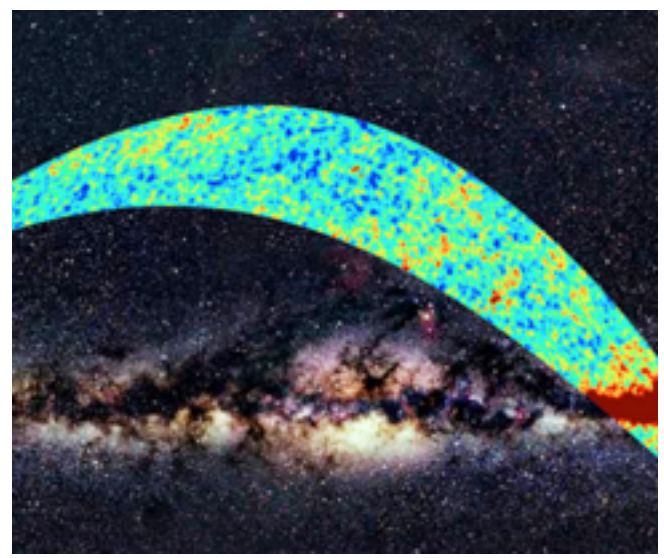
Cosmology of the Dirac-Milne Universe







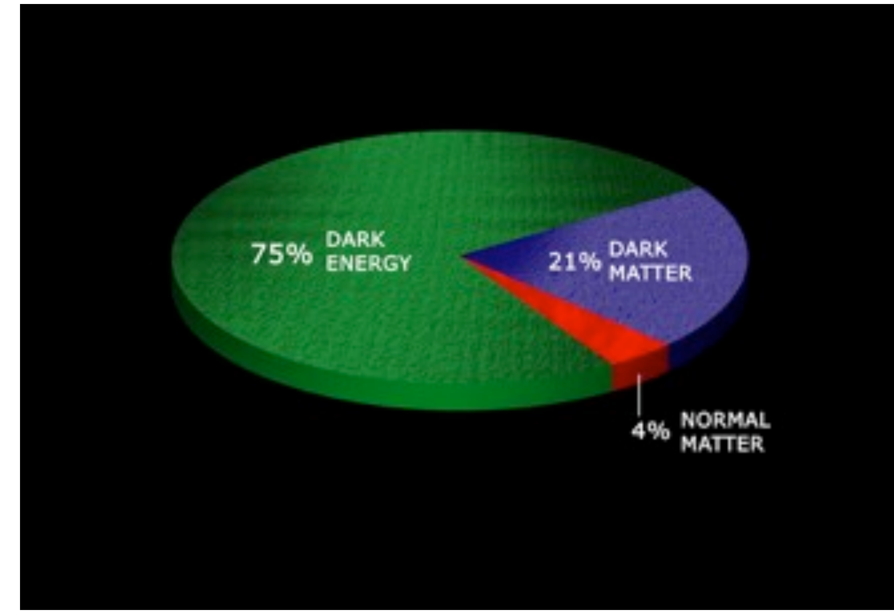
Aurélien Benoit-Lévy
Institut d'Astrophysique de Paris
in collaboration with Gabriel Chardin

Benoit-Lévy, Chardin, A&A, *accepted*

Antimatter and Gravitation - Paris - October 2011

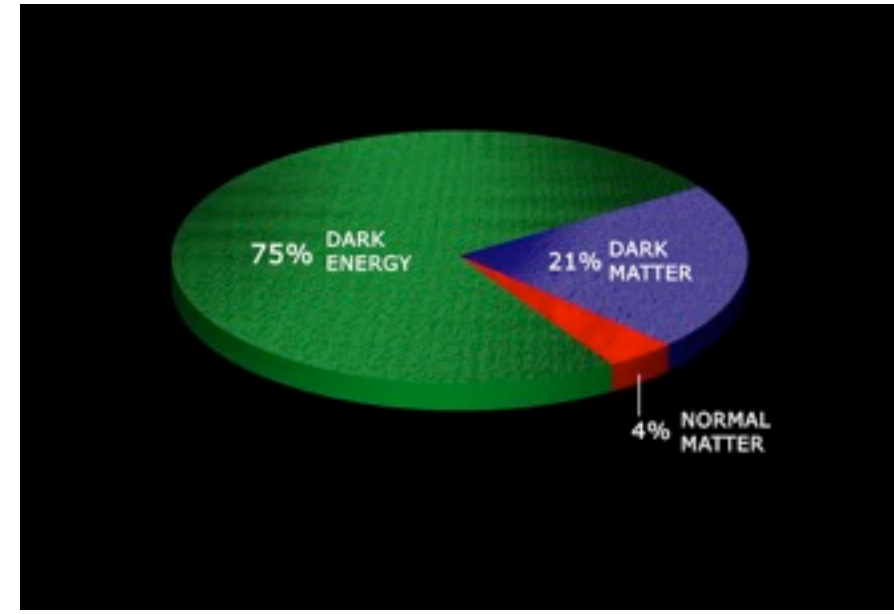
Motivation for alternative models

- **95% of our Universe escapes our knowledge**

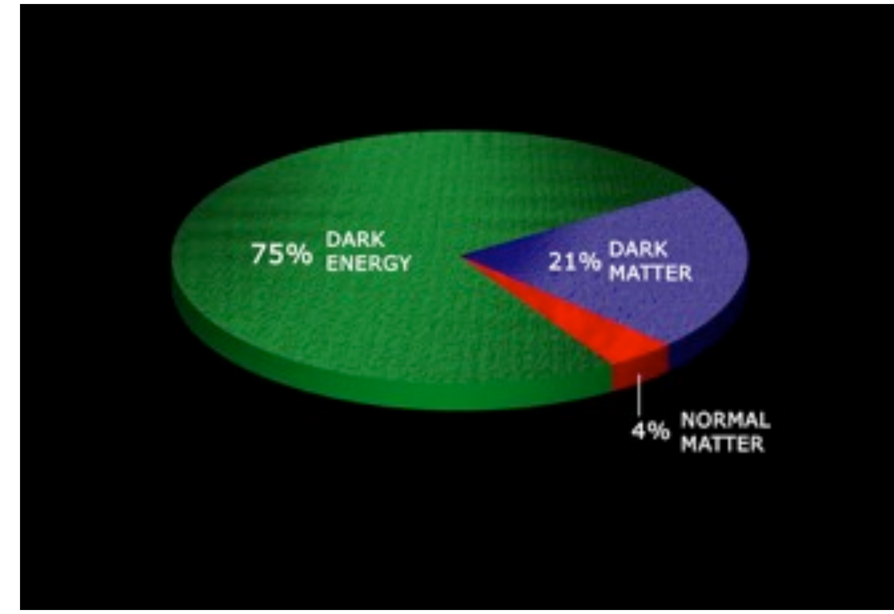


Motivation for alternative models

- **95% of our Universe escapes our knowledge**
- **Dark Energy**
  - True cosmological constant: why this value?
  - Vacuum energy: 10^{120} times smaller than expected
  - "Coincidence problem"

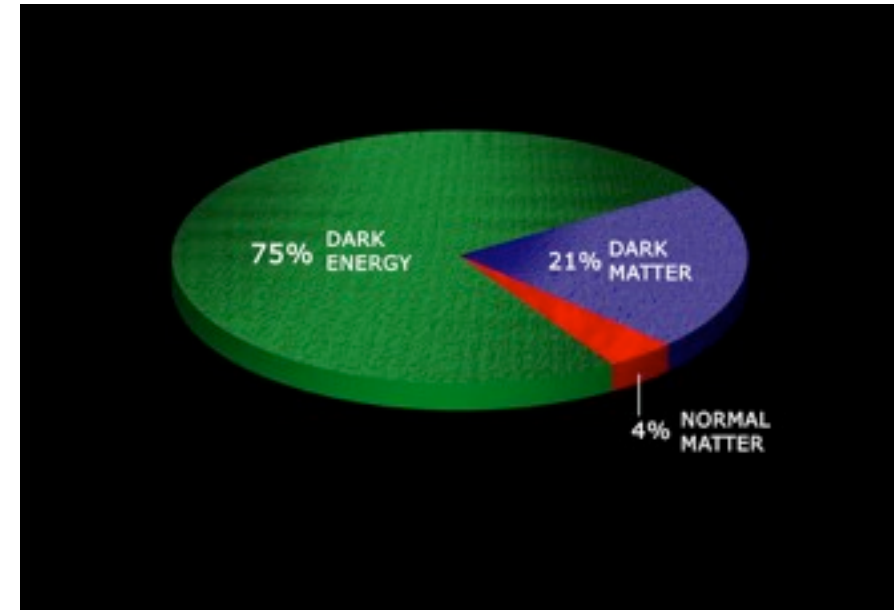


Motivation for alternative models



- **95% of our Universe escapes our knowledge**
- **Dark Energy**
  - True cosmological constant: why this value?
  - Vacuum energy: 10^{120} times smaller than expected
  - "Coincidence problem"
- **Dark Matter**
  - Baryon content from Standard Big-Bang nucleosynthesis not sufficient
  - Still escapes direct detection

Motivation for alternative models



- **95% of our Universe escapes our knowledge**
- **Dark Energy**
  - True cosmological constant: why this value?
  - Vacuum energy: 10^{120} times smaller than expected
  - "Coincidence problem"
- **Dark Matter**
  - Baryon content from Standard Big-Bang nucleosynthesis not sufficient
  - Still escapes direct detection
- **Inflation**
  - Introduced to solve horizon and flatness problem

Standard model relies on 3 ingredients which are undetected and /or not understood

Motivation for negative mass

Matter - antimatter symmetric Universe

Antimatter is supposed to have a negative active gravitational mass

Motivation for negative mass

Matter - antimatter symmetric Universe

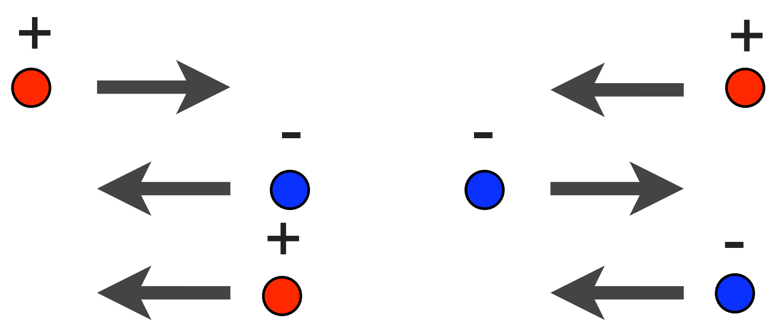
Antimatter is supposed to have a negative active gravitational mass

Antimatter naturally comes as negative mass candidate from Kerr-Newman solution

- When $(q, m, ma) = \left(-e, m_e, \frac{\hbar}{2}\right)$ then two $\mathbb{R}^4$ connected by the annular singularity
- Solution is symmetric under $(r, e, m) \leftrightarrow (-r, -e, -m)$
- In the second space, the solution is seen as having reversed charge and mass (Carter 68)
- This strongly suggests antimatter!
- Also implies that cannot create negative mass as independent degree of freedom

Negative mass in General Relativity

- "Runaway" solution (Bondi 57)



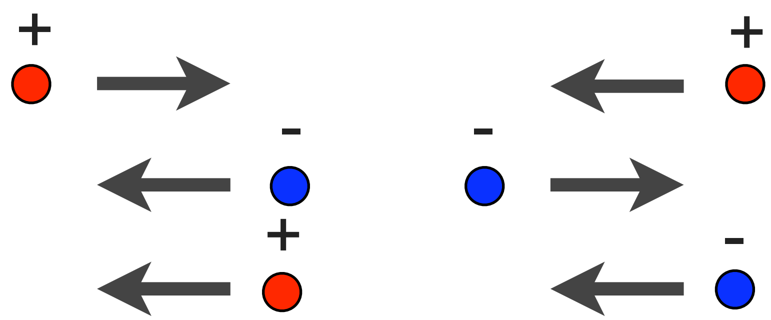
If antimatter is Bondi-type negative mass, antihydrogen weighting experiments should see antimatter fall as matter

- Corresponds to negative inertial mass
- This would lead to incompatible annihilations

<u>To have a viable cosmology, we need mutual repulsion between matter and antimatter</u>

Negative mass in General Relativity

- “Runaway” solution (Bondi 57)



If antimatter is Bondi-type negative mass, antihydrogen weighting experiments should see antimatter fall as matter

  - Corresponds to negative inertial mass
  - This would lead to incompatible annihilations

<u>To have a viable cosmology, we need mutual repulsion between matter and antimatter</u>

- Electron-hole analogy: antimatter seen as hole. Goes up in a gravitational field.
  - “Electron bubble” in superfluid helium; bubble accelerated upwards with 2g
  - Voids in large-scale structures seen as negative density with respect to background density (Dubinski et al. 93, Piran 97). What if background density is null?

Properties of the Dirac-Milne universe

- Flat space-time, open space

$$T_{\mu\nu} = 0 \Longleftrightarrow a(t) = t \text{ and } k = -1$$

Properties of the Dirac-Milne universe

- **Flat space-time, open space**

$$T_{\mu\nu} = 0 \Longleftrightarrow a(t) = t \text{ and } k = -1$$

- **Linear evolution with time of the scale factor**
  - no acceleration (and no deceleration) of the expansion
  - a linear scale factor during the whole history of the Universe solves the horizon problem

Properties of the Dirac-Milne universe

- **Flat space-time, open space**

$$T_{\mu\nu} = 0 \Longleftrightarrow a(t) = t \text{ and } k = -1$$

- **Linear evolution with time of the scale factor**
  - no acceleration (and no deceleration) of the expansion
  - a linear scale factor during the whole history of the Universe solves the horizon problem
  - time - temperature relation $$T = \frac{T_0}{H_0}\frac{1}{t}$$

	Standard Model	Dirac-Milne	Ratio
T= 170 MeV	3×10^{-5} sec	7 days	1.7×10^{10}
T = 1 MeV	1 sec	3.3 yr	1×10^{8}
T = 80 keV	~200 sec	41 yr	6.5×10^{6}
T = 3000 K	380 000 yr	12×10^{6} yr	32
$T = T_0$	$\sim H_0^{-1}$	H_0^{-1}	~ 1

Properties of the Dirac-Milne universe

- **Flat space-time, open space**

$$T_{\mu\nu} = 0 \Longleftrightarrow a(t) = t \text{ and } k = -1$$

- **Linear evolution with time of the scale factor**
  - no acceleration (and no deceleration) of the expansion
  - a linear scale factor during the whole history of the Universe solves the horizon problem
  - time - temperature relation $$T = \frac{T_0}{H_0}\frac{1}{t}$$

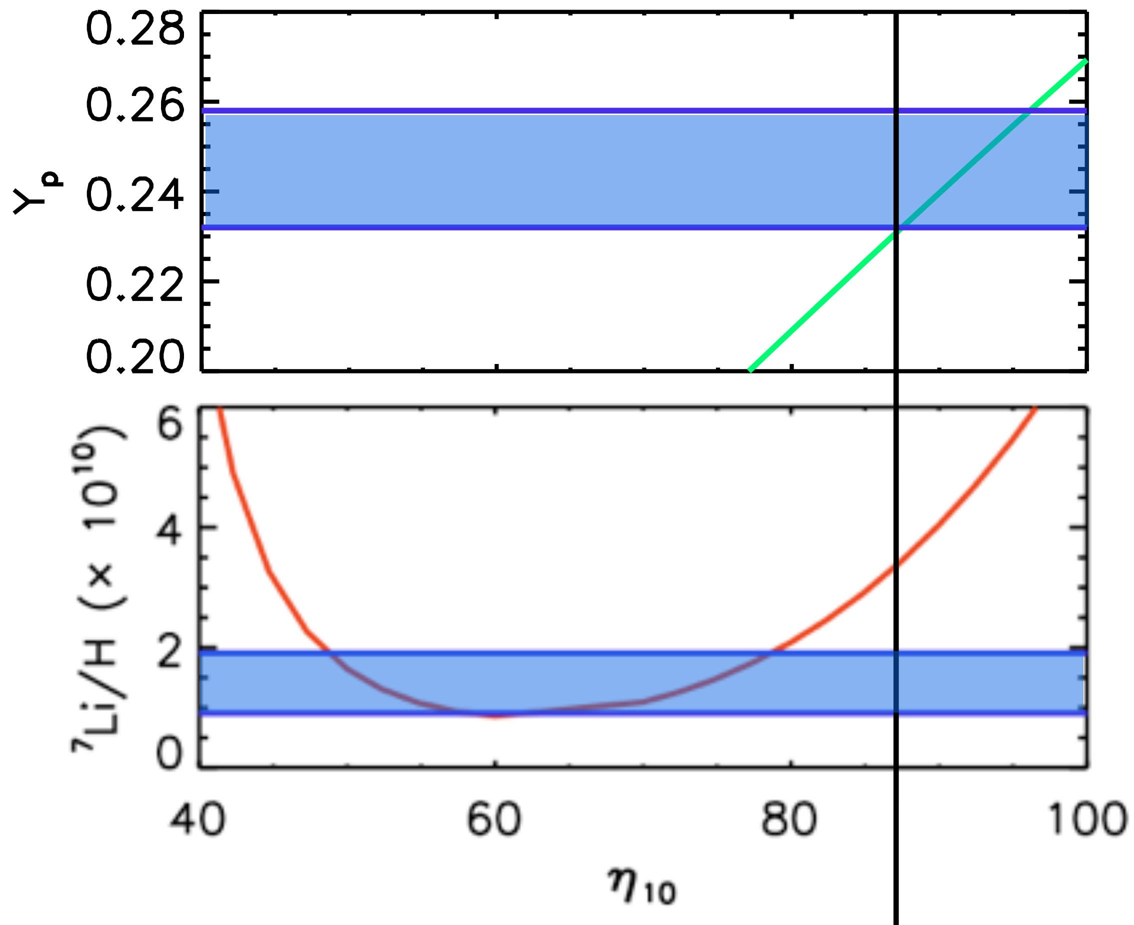
	Standard Model	Dirac-Milne	Ratio
T= 170 MeV	3×10^{-5} sec	7 days	1.7×10^{10}
T = 1 MeV	1 sec	3.3 yr	1×10^{8}
T = 80 keV	~200 sec	41 yr	6.5×10^{6}
T = 3000 K	380 000 yr	12×10^{6} yr	32
T= T_0	~ H_0^{-1}	H_0^{-1}	~ 1

No inflation needed to solve the horizon problem

No Dark Energy needed to solve the age problem

Primordial Nucleosynthesis

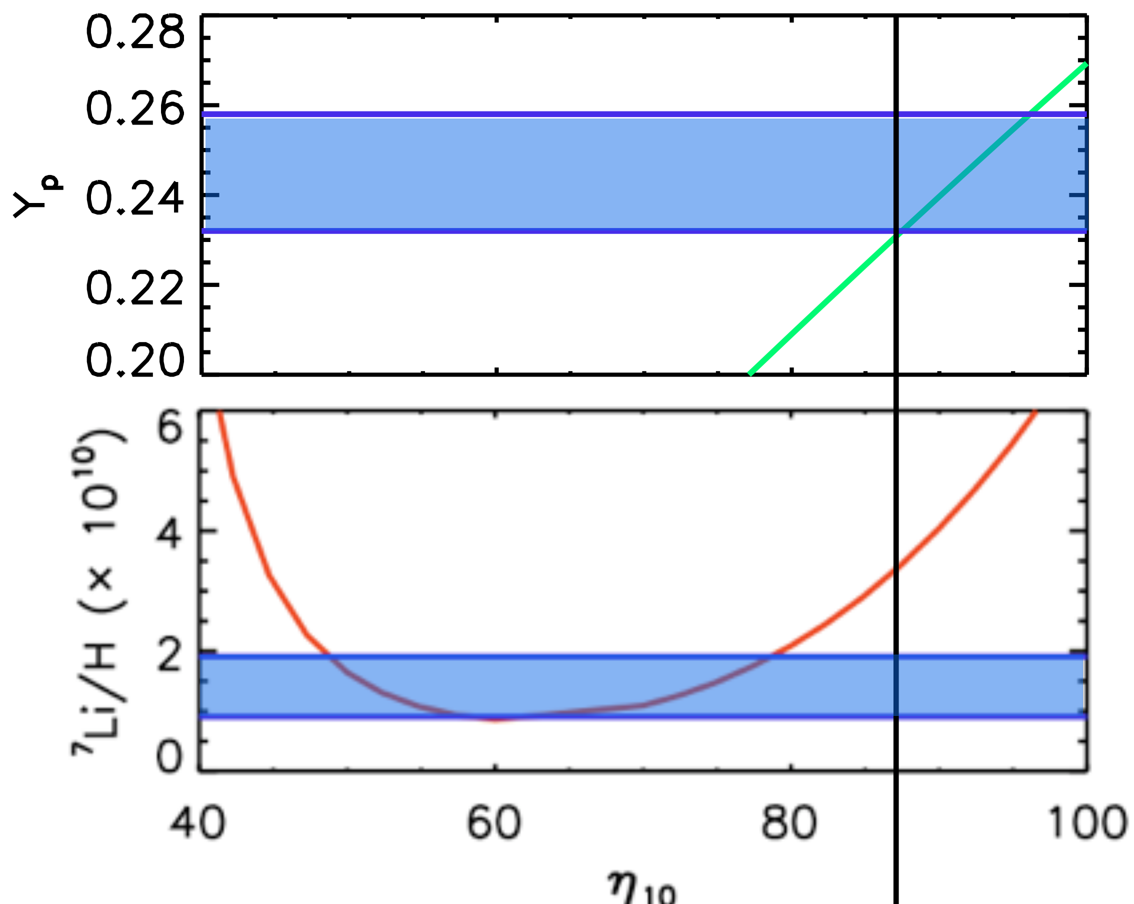
- **Thermal episode : production of ^{4}He and ^{7}Li** (Lohiya *et al*. 98 & Kaplinghat *et al.* 00, ABL & Chardin 11)
  - Late decoupling of weak reactions, lead to ^{4}He and ^{7}Li



$$\frac{^7\mathrm{Li}}{\mathrm{H}} = 3.45 \times 10^{-10}$$

Primordial Nucleosynthesis

- **Thermal episode : production of ^{4}He and ^{7}Li** (Lohiya *et al*. 98 & Kaplinghat *et al.* 00, ABL & Chardin 11)
  - Late decoupling of weak reactions, lead to ^{4}He and ^{7}Li



$$\frac{^{7}\mathrm{Li}}{\mathrm{H}} = 3.45 \times 10^{-10}$$

$$8.8 \times 10^{-9} < \eta < 9.6 \times 10^{-9}$$

$$\Downarrow$$

No non-baryonic matter is a priori needed

Primordial Nucleosynthesis

- **Thermal episode : production of ^4He and ^7Li** (Lohiya *et al*. 98 & Kaplinghat *et al.* 00, ABL & Chardin 11)
  - Late decoupling of weak reactions, lead to ^4He and ^7Li
  - D and ^3He are totally destroyed by this thermal process

Primordial Nucleosynthesis

- **Thermal episode : production of ^{4}He and ^{7}Li** (Lohiya *et al*. 98 & Kaplinghat *et al.* 00, ABL & Chardin 11)
  - Late decoupling of weak reactions, lead to ^{4}He and ^{7}Li
  - D and ^{3}He are totally destroyed by this thermal process

- **D and ^{3}He production by photodisintegration of ^{4}He** (ABL & Chardin 11)
  - Annihilation at the border of domains
  - D and ^{3}He final abondances as function of the typical size of domains
  - Annihilation at the border of domains

$$\bar{\mathrm{p}} + \mathrm{p} \rightarrow \gamma + \alpha \rightarrow \mathrm{D},^3\mathrm{He},^3\mathrm{H}$$

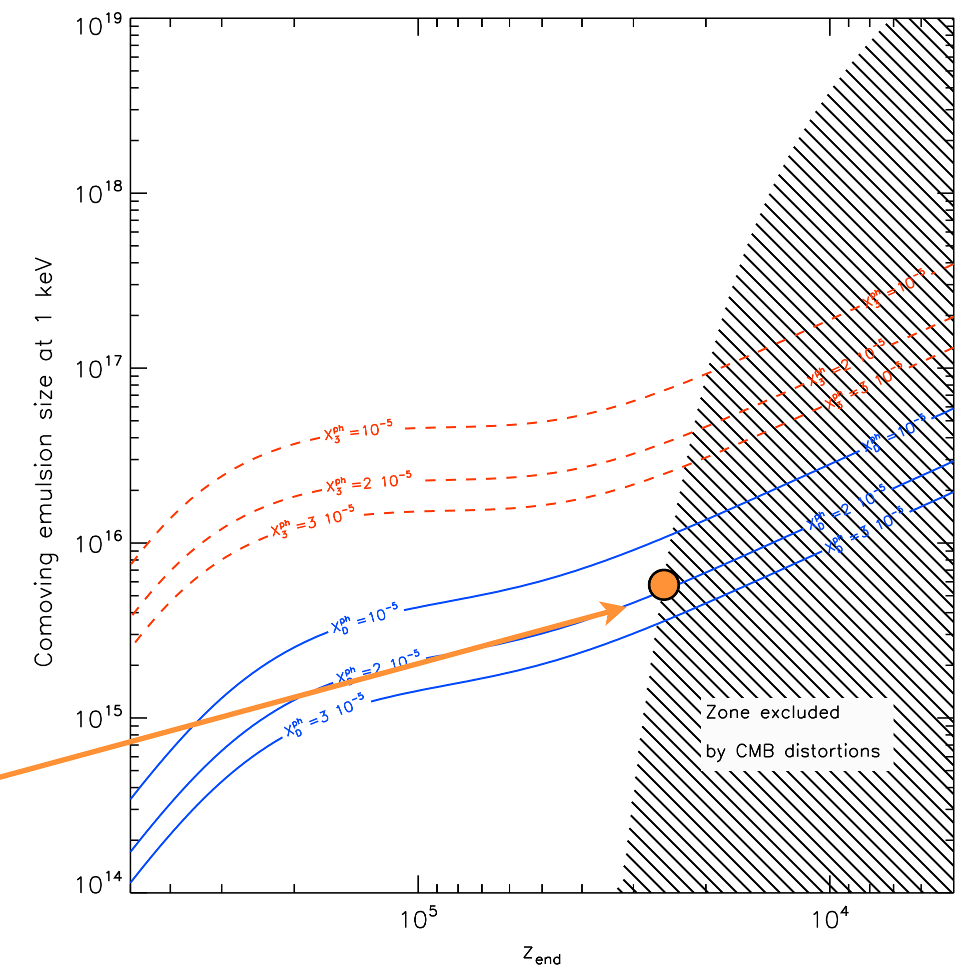
Primordial Nucleosynthesis

- **Thermal episode : production of ^{4}He and ^{7}Li** (Lohiya *et al*. 98 & Kaplinghat *et al*. 00, ABL & Chardin 11)
  - Late decoupling of weak reactions, lead to ^{4}He and ^{7}Li
  - D and ^{3}He are totally destroyed by this thermal process

- **D and ^{3}He production by photodisintegration of ^{4}He** (ABL & Chardin 11)
  - Annihilation at the border of domains
  - D and ^{3}He final abondances as function of the typical size of domains
  - Annihilation at the border of domains

$$\bar{\mathrm{p}} + \mathrm{p} \rightarrow \gamma + \alpha \rightarrow \mathrm{D}, ^3\mathrm{He}, ^3\mathrm{H}$$

  - Domain size ~7 kpc comoving, but size at the moment of production. Will evolve after recombination
  - ^{3}He/D >> 1, possibly a constraint as ^{3}He/D is observed <1 (Sigl *et al*. 95)



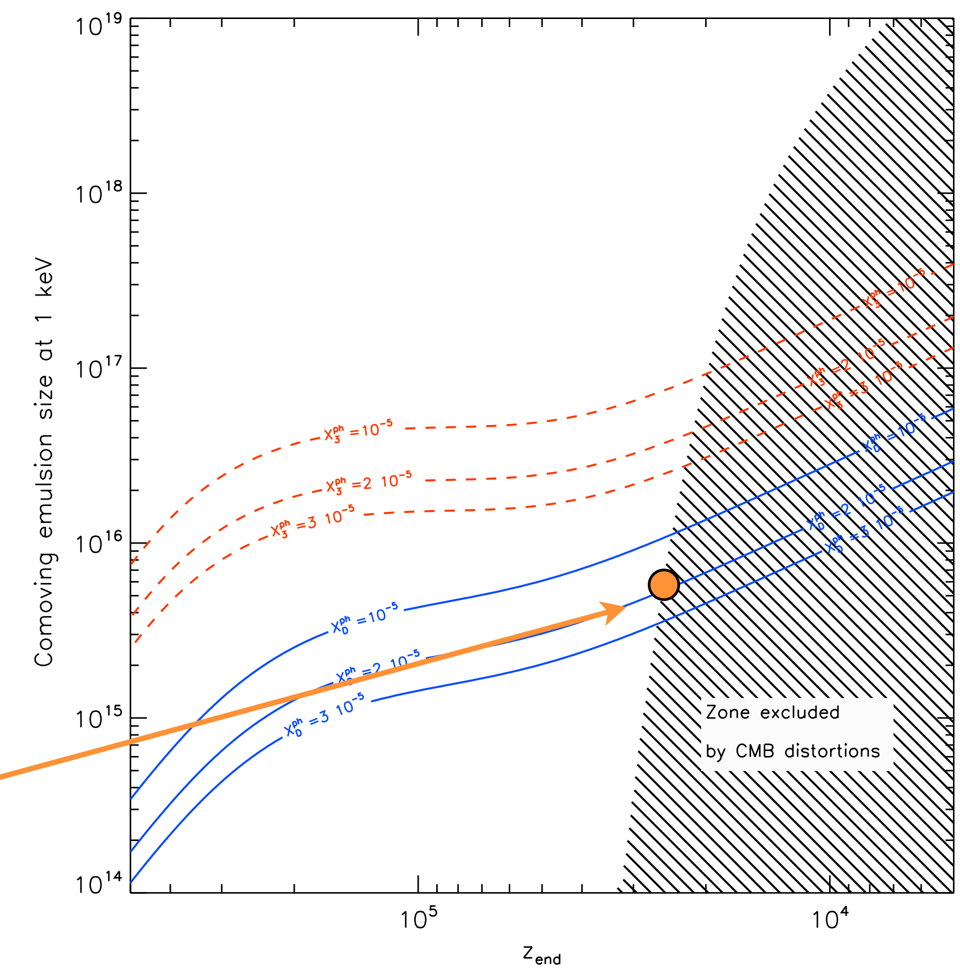
Primordial Nucleosynthesis

- **Thermal episode : production of ^{4}He and ^{7}Li** (Lohiya *et al*. 98 & Kaplinghat *et al*. 00, ABL & Chardin 11)
  - Late decoupling of weak reactions, lead to ^{4}He and ^{7}Li
  - D and ^{3}He are totally destroyed by this thermal process

- **D and ^{3}He production by photodisintegration of ^{4}He** (ABL & Chardin 11)
  - Annihilation at the border of domains
  - D and ^{3}He final abondances as function of the typical size of domains
  - Annihilation at the border of domains

$$\bar{\mathrm{p}} + \mathrm{p} \rightarrow \gamma + \alpha \rightarrow \mathrm{D}, {}^3\mathrm{He}, {}^3\mathrm{H}$$

  - Domain size ~7 kpc comoving, but size at the moment of production. Will evolve after recombination
  - ^{3}He/D >> 1, possibly a constraint as ^{3}He/D is observed <1 (Sigl *et al*. 95)



BBN compatible with D, ^{4}He, ^{7}Li tension with ^{3}He

Type Ia Supernovae

Historical discovery of acceleration of expansion

- Riess *et al.* 98 & Perlmutter *et al.* 99 discovered that distant SN Ia are dimmer than expected
- Interpretation that the expansion is accelerating under the effect of Dark Energy
- Confirmed by other experiments (e.g. SNLS)
- won 2011 Nobel prize

Type Ia Supernovae

Historical discovery of acceleration of expansion

- Riess *et al.* 98 & Perlmutter *et al.* 99 discovered that distant SN Ia are dimmer than expected
- Interpretation that the expansion is accelerating under the effect of Dark Energy
- Confirmed by other experiments (e.g. SNLS)
- won 2011 Nobel prize

But

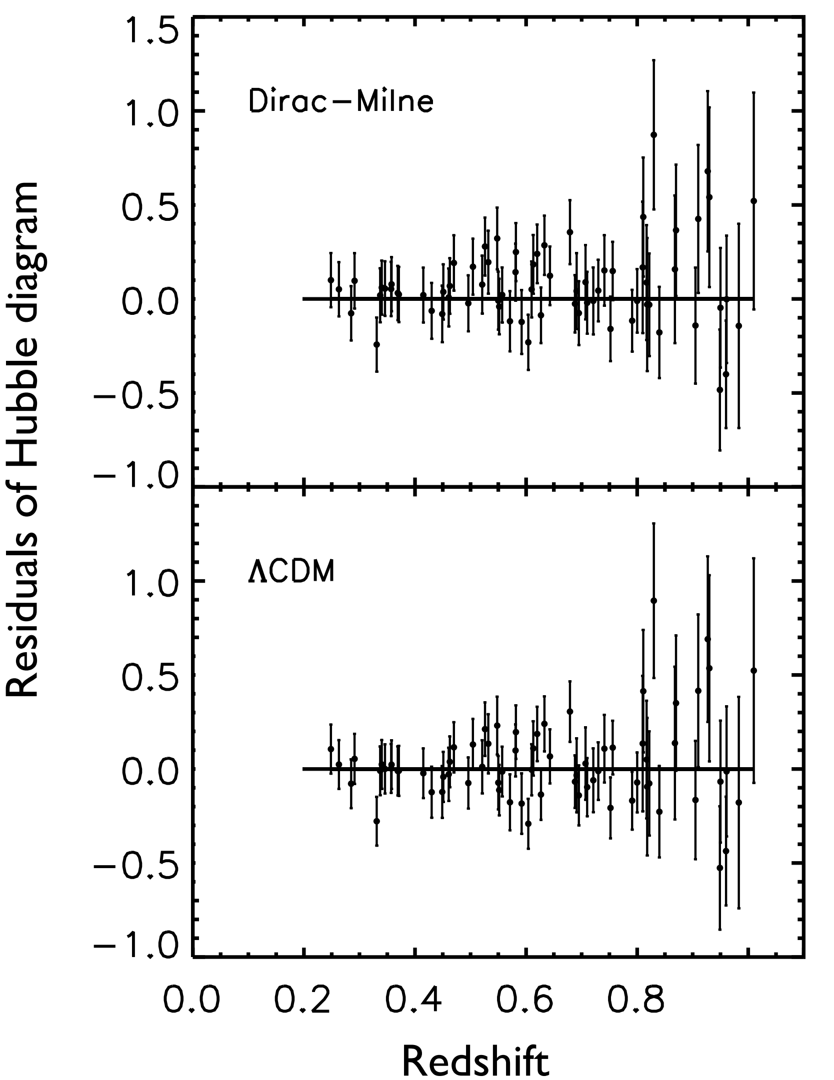
- Dirac-Milne universe does not present acceleration (nor deceleration) of the expansion

Type Ia Supernovae

Historical discovery of acceleration of expansion

- Riess *et al.* 98 & Perlmutter *et al.* 99 discovered that distant SN Ia are dimmer than expected
- Interpretation that the expansion is accelerating under the effect of Dark Energy
- Confirmed by other experiments (e.g. SNLS)
- won 2011 Nobel prize

SNLS data (Astier *et al.* 06)



But

- Dirac-Milne universe does not present acceleration (nor deceleration) of the expansion
- With only high-z SNe Ia, Dirac-Milne is as good as ΛCDM.

Type Ia Supernovae

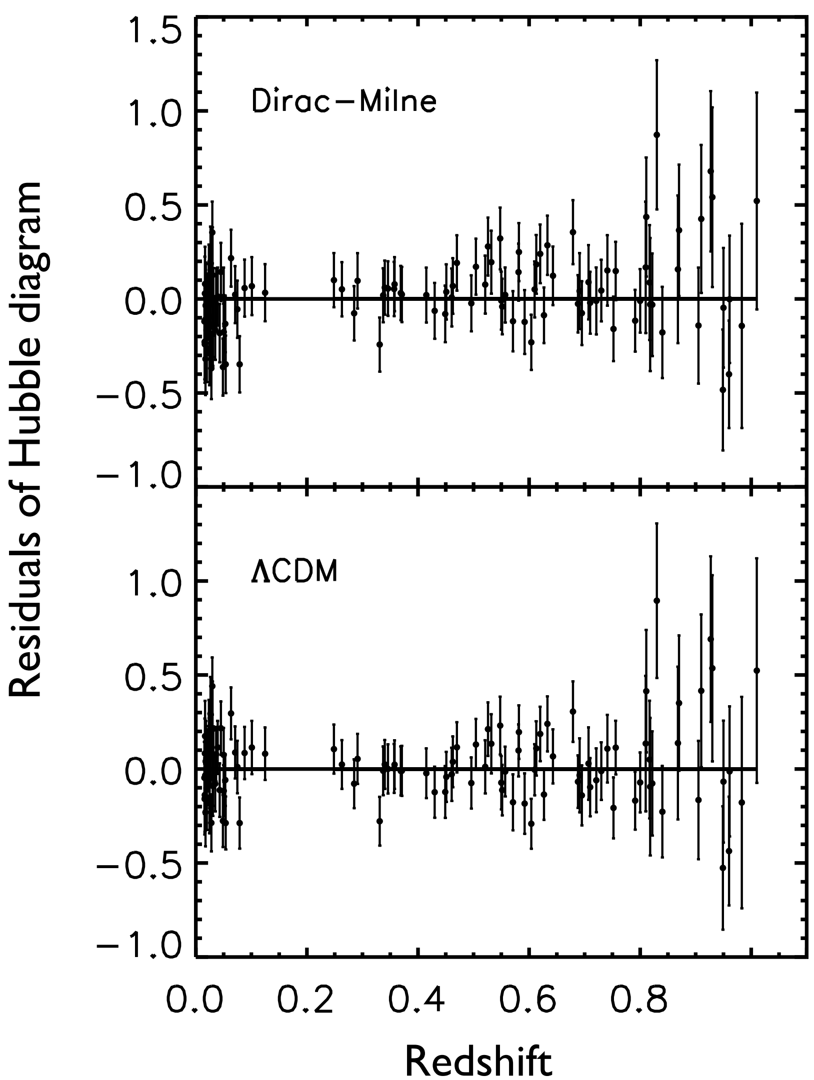
Historical discovery of acceleration of expansion

- Riess *et al.* 98 & Perlmutter *et al.* 99 discovered that distant SN Ia are dimmer than expected
- Interpretation that the expansion is accelerating under the effect of Dark Energy
- Confirmed by other experiments (e.g. SNLS)
- won 2011 Nobel prize

But

- Dirac-Milne universe does not present acceleration (nor deceleration) of the expansion
- With only high-z SNe Ia, Dirac-Milne is as good as ΛCDM.
- Nearby SN Ia are crucial

SNLS data (Astier *et al.* 06)

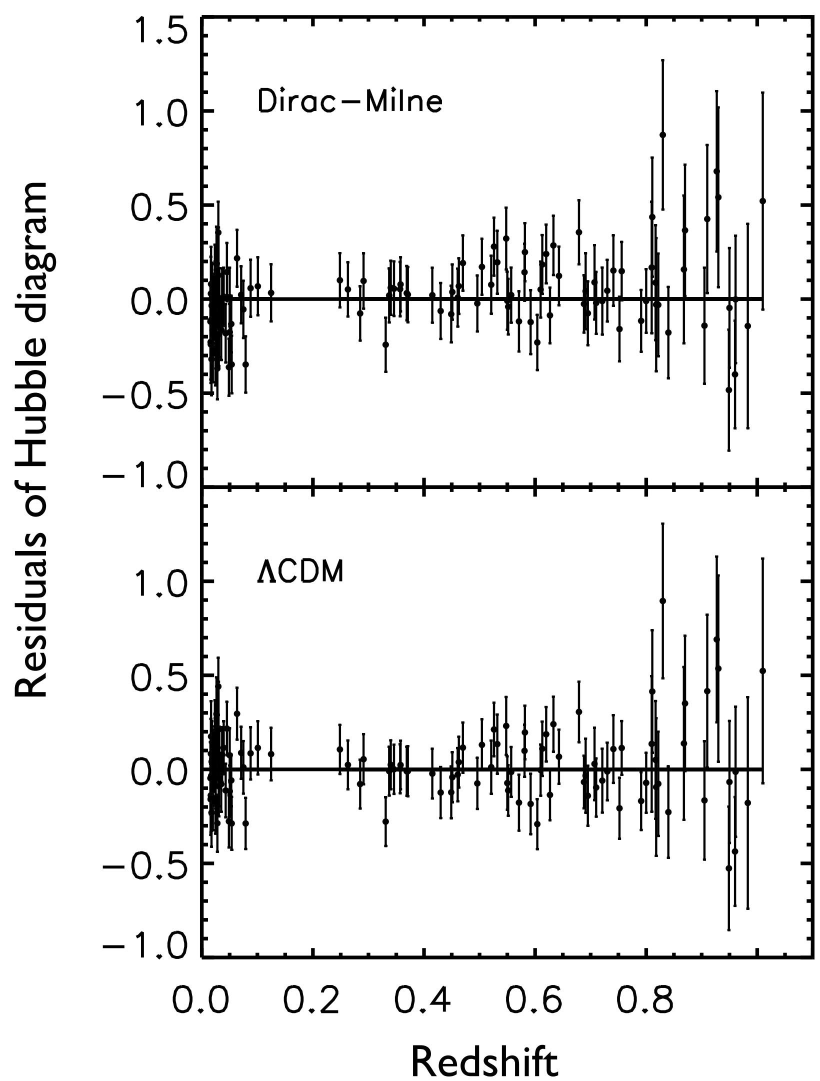


Type Ia Supernovae

Historical discovery of acceleration of expansion

- Riess *et al.* 98 & Perlmutter *et al.* 99 discovered that distant SN Ia are dimmer than expected
- Interpretation that the expansion is accelerating under the effect of Dark Energy
- Confirmed by other experiments (e.g. SNLS)
- won 2011 Nobel prize

SNLS data (Astier *et al.* 06)



But

- Dirac-Milne universe does not present acceleration (nor deceleration) of the expansion
- With only high-z SNe Ia, Dirac-Milne is as good as ΛCDM.
- Nearby SN Ia are crucial
- An offset on low-z SNe Ia by $\Delta m = 0.06 \text{ mag}$ makes the χ^2 equal

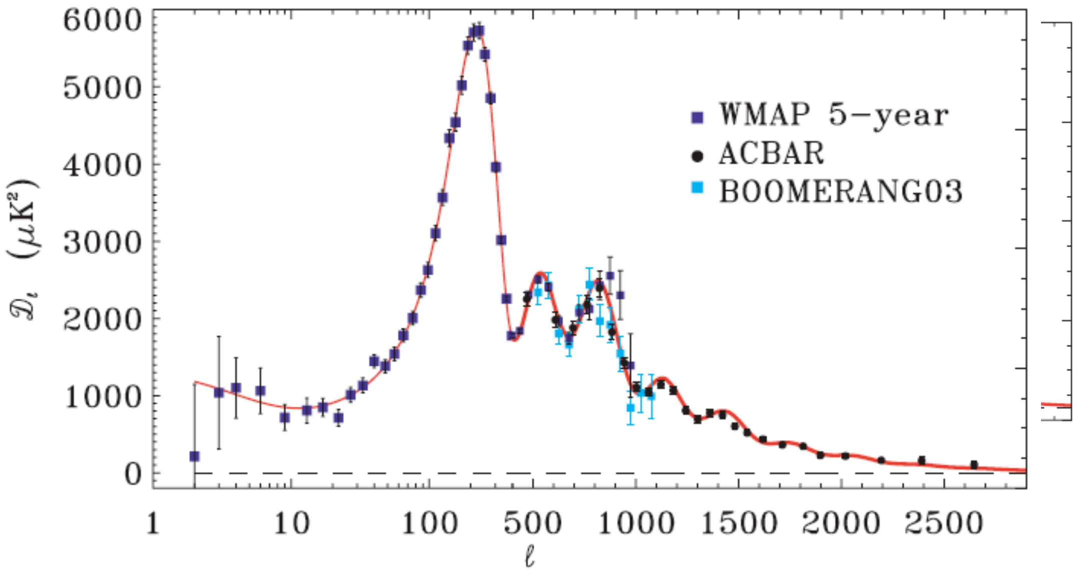
Kowalski *et al.* 08 estimate σ_{sys}=0.04 mag

Dirac-Milne universe close to best-fit

First steps on Cosmic Microwave Background

- **CMB: major test of cosmological models**
  - First peak corresponds to acoustic scale given by sound horizon seen on last scattering surface.

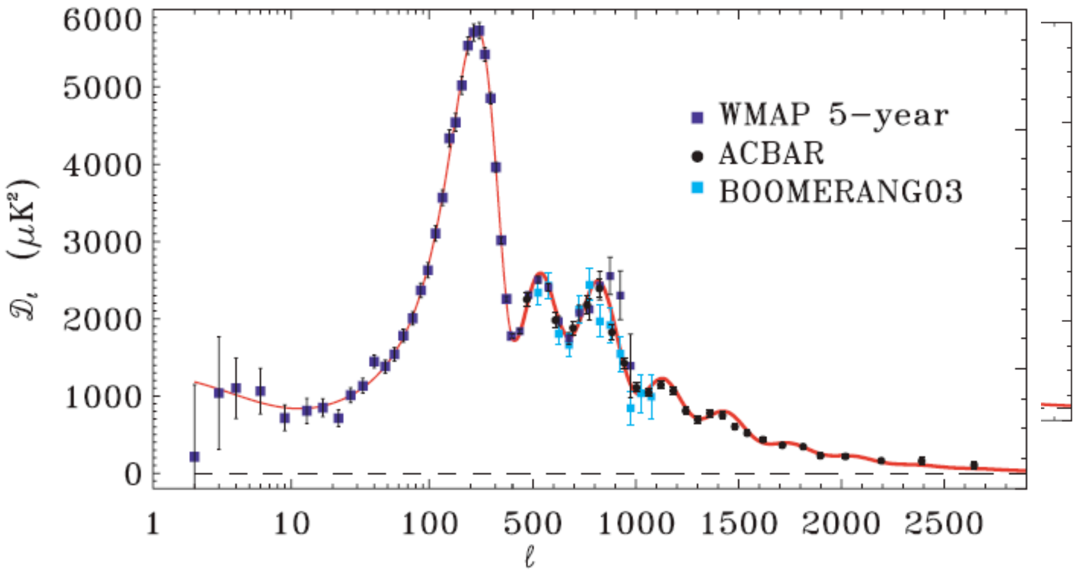
$$\boxed{\theta = \frac{r_s}{d_A}}$$



First steps on Cosmic Microwave Background

- **CMB: major test of cosmological models**
  - First peak corresponds to acoustic scale given by sound horizon seen on last scattering surface.

$$\boxed{\theta = \frac{r_s}{d_A}}$$



  - For Dirac-Milne, angular distance

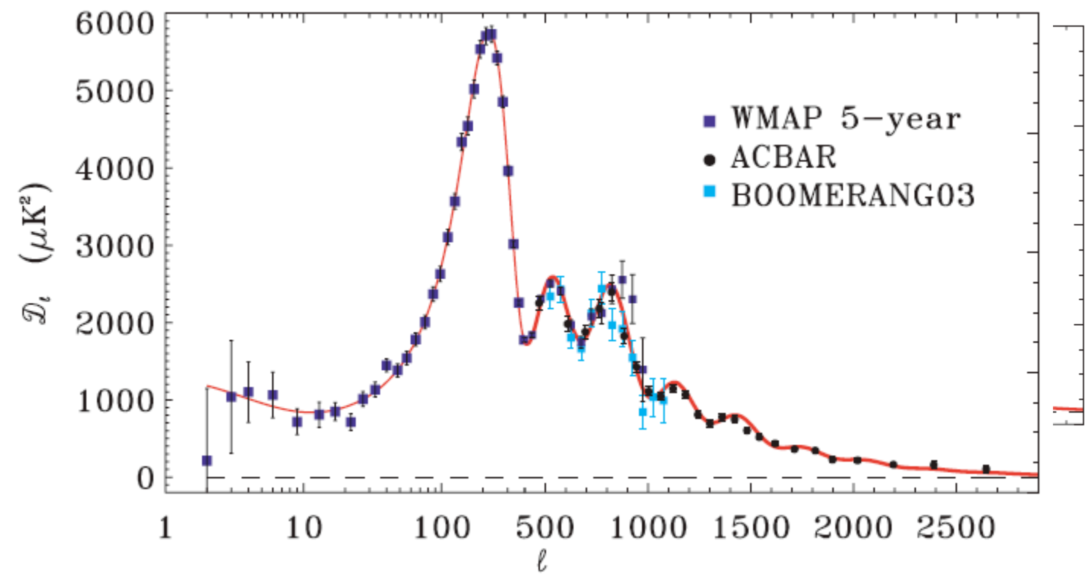
$$d_A(z) = H_0^{-1} \frac{1}{1+z} \sinh(\ln(1+z))$$

is 163 times larger than in ΛCDM.

<u>one would expect a tiny angle!</u>

First steps on Cosmic Microwave Background

- **CMB: major test of cosmological models**



  - First peak corresponds to acoustic scale given by sound horizon seen on last scattering surface.

$$\boxed{\theta = \frac{r_s}{d_A}}$$

  - For Dirac-Milne, angular distance

$$d_A(z) = H_0^{-1} \frac{1}{1+z} \sinh(\ln(1+z))$$

is 163 times larger than in ΛCDM.

<u>one would expect a tiny angle!</u>

  - But, due to linear scale factor, sound horizon is much larger than in standard model

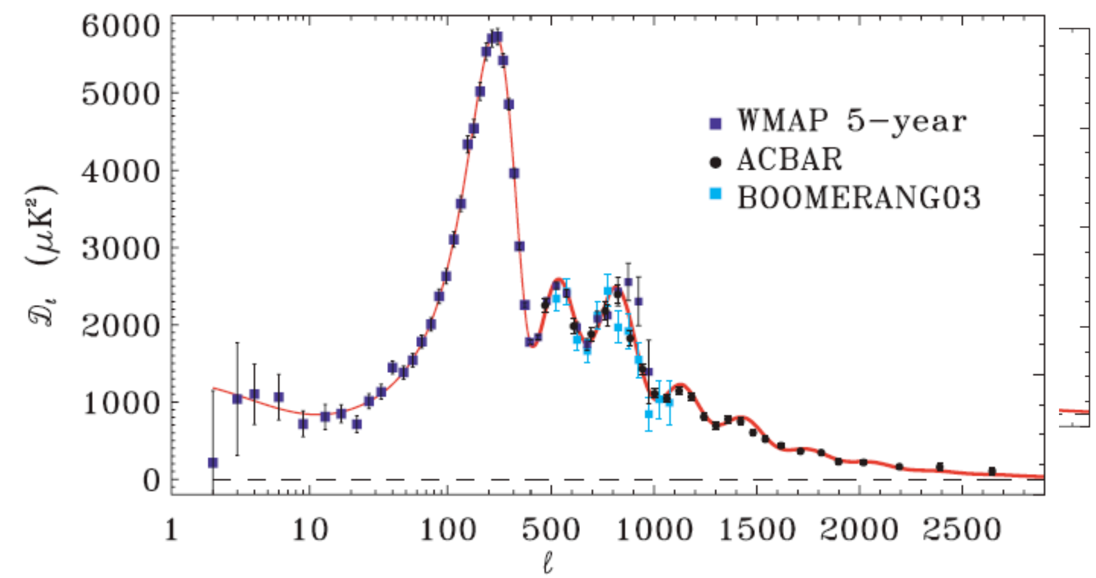
$$r_s = \int c_s \frac{dt'}{a(t')}$$

Integrating from 40 MeV to ~7 eV (end of annihilation, cf BBN) yields acoustic scale around 1° !

First steps on Cosmic Microwave Background

- **CMB: major test of cosmological models**
  - First peak corresponds to acoustic scale given by sound horizon seen on last scattering surface.

$$\boxed{\theta = \frac{r_s}{d_A}}$$



  - For Dirac-Milne, angular distance

$$d_A(z) = H_0^{-1} \frac{1}{1+z} \sinh(\ln(1+z))$$ is 163 times larger than in ΛCDM.

<u>one would expect a tiny angle!</u>

  - But, due to linear scale factor, sound horizon is much larger than in standard model

$$r_s = \int c_s \frac{dt'}{a(t')}$$

Integrating from 40 MeV to ~7 eV (end of annihilation, cf BBN) yields acoustic scale around 1º !

Acoustic scale naturally emerges at 1º

Conclusion

- **Dirac-Milne universe**
  - Symmetric matter - antimatter universe
  - Antimatter is supposed to have a negative active gravitational mass
- **In fair agreement with studied cosmological tests**
  - Thermal primordial nucleosynthesis of ^{4}He and ^{7}Li
    Secondary production of D can constrain size of the matter-antimatter emulsion
    ^{3}He production too high
  - Taken at face value, SNe Ia data favour accelerating universe
    Dirac-Milne universe requires reasonable systematic errors
  - Acoustic scale naturally expected at the degree scale in CMB
- **Still, many uncovered issues**
  - Disagrement on Baryonic Acoustic Oscillations (BAO)
  - Structure formation
  - CMB anisotropies
  - ...